(2)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

AD-A210 977

(S)

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release;
distribution unlimited.

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Research Laboratory of Electronics
Massachusetts Institute of Technology

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
77 Massachusetts Avenue
Cambridge, MA 02139

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
U.S. Army Research Office

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
DAAL03-88-K-0108

8c. ADDRESS *(City, State, and ZIP Code)*
P.O. Box 12211
Research Triangle Park, NC 27709

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
	P-26051-E	L	

11. TITLE *(Include Security Classification)*
Focused Ion Beam Implantation

12. PERSONAL AUTHOR(S)
J. Melngailis

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Semi-Annual	FROM 1-1-89 TO 6-30-89	7-13-89	7 pages

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Work by J. Melngailis and his collaborators is summarized here.

89 032

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Mary Greene - RLE Contract Reports

22b. TELEPHONE *(Include Area Code)*
(617)258-5871

22c. OFFICE SYMBOL

26051-EL

PROGRESS REPORT

TWENTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 26051-EL

2. PERIOD COVERED BY REPORT: 1 January 1989 - 30 June 1989

3. TITLE OF PROPOSAL: Focus ed Ion Beam Implantation

4. CONTRACT OR GRANT NUMBER: DAAL03-88-K-0108

5. NAME OF INSTITUTION: Massachusetts Institute of Technology

6. AUTHORS OF REPORT: John Melngailis

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

J. Melngailis, "Focused Ion Beam Lithography and Implantation". Proceedings of 8th University/Government/Industry *Microelectronic Symposium*. Westboro, MA June 1989 (Pub. IEEE).

W. Chu, A. Yen, K. Ismail, M.I. Shepard, H.J. Lezec, C.R. Musil, J. Melngailis, Y.-C. Ku, J.M. Carter, and H.I. Smith, "Sub 100 nm X-ray Mask Technology Using Focused Ion Beam Lithography". Submitted to J. Vac. Sci. Technol. B (presented at the Electron, Ion and Photon Beam Symposium, Monterey, May 1989).

K. Ismail, W. Chu, R.T. Tiberio, A. Yen, H.J. Lezec, M.I. Shepard, C.R. Musil, J. Melngailis, D.A. Antoniadis, and H.I. Smith, "Resonant Tunneling Across and Mobility Modulation Along Surface-Structured Quantum Wells". Submitted to J. Vac. Sci. Technol. B (presented at the Electron, Ion and Photon Beam Symposium, Monterey, May 1989).

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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"Focused Ion Beam Implantation"

Progress Report

Jan. 1, 1989 - June 30, 1989

by John Melngailis

ARO (DARPA)

Contract No. DAAL03-88-K-0108

Brief Outline of Research Findings

During the reporting period covering the first six months of 1989, pattern translation capability has been developed and used to implant Si NMOS devices and Gunn diodes.

1. The capability to transfer the positions of features from a given level of an integrated circuit layout to the focused ion beam machine is important in most of the intended applications of focused ion beam implantation. We have developed the capability to transfer patterns written in MAGIC (a layout software system) to the focused ion beam format. The "label scheme", which permits additional information, besides the location and size of features, to be transmitted, is used to specify the ion dose in a given feature. Dose gradients can also be specified.

   In addition, routines to calibrate the focused ion beam deflection and to accurately align the sample to the focused ion beam field have been developed.

2. The machine development described above was used to implant the channels on Si-NMOS devices. A test structure was used where each die had 256 transistors each one with probe contact pads. Each die was aligned to the focused ion beam and then all 256 channels were implanted with a variety of doses and geometrics. In some dies boron stripes were implanted next to the source. This produced a 25% increase in transconductance and a large increase in output impendence resulting in an increase in gain of a factor of 20.

In other devices As was implanted with a gradient of doping from source to drain.

3. In the area of GaAs devices, Gunn diodes were implanted with variety of doping gradients between the contacts. Again the pattern transfer and alignment capability was used. The doping gradients were chosen according to calculated computer models. The conventional fabrication steps (annealing and contacts) are being completed.

In addition, a mask set has been fabricated for the fabrication of GaAs MESFET's. The channel regions will be implanted with various doses of Si in various geometrics. Submicron length gates, aligned to the focused ion beam implants, will be defined by using focused ion beam lithography.

4. We have also collaborated with H.I. Smith and his colleagues to use the fine pattern writing of the focused ion beam system to generate electrodes on GaAs/GaAlAs modulation doped structures. These electrodes had a minimum width of 0.05 µm and were used to observe resonant tunneling parallel to the surface.

Submitted to J. Vac. Sci. Tech.
June 1989

Sub-100 nm X-ray Mask Technology Using Focused-Ion-Beam Lithography

by

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J. Melngailis, Y.-C. Ku, J.M. Carter, and Henry I. Smith
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Abstract

In the past, nearly all x-ray nanolithography (i.e., sub-100 nm linewidths) employed the C_K x-ray line at 4.5 nm. This, in turn, necessitated near-zero gaps (to avoid diffraction) and carbonaceous masks (e.g., polyimide, which is subject to distortion). In order to use x-ray replication in the fabrication of multilevel devices and circuits that cover large areas (~ a few cm^2) and have feature sizes well below 100 nm, we have turned to the Cu_L line at 1.3 nm. Masks consist of 1 µm-thick Si or Si_3N_4 membranes and Au absorber patterns, 200 nm thick, which provide 10 db contrast. Linewidths < 50 nm have been replicated, indicating that photoelectron range is not a serious problem. Focused-ion-beam-lithography (FIBL) with Be^{++} ions at 280 keV was used to produce quantum-effect-device patterns with minimum linewidths down to ~50 nm. The FIBL process (exposure of 300 nm-thick PMMA, followed by Au electroplating) is high yield and much simpler than a tri-level electron-beam-lithography process designed to give comparable results. This is the first time FIBL has been used to make x-ray masks at sub-100 nm linewidths. Along with the device patterns, linear-zone-plate alignment marks were also written on the masks, to be aligned to corresponding marks on the substrate via an optical alignment scheme. In this paper we report on procedures for fabricating and aligning the new x-ray nanolithography masks, and show results of exposures.

Introduction

X-ray lithography has been used in the fabrication of a wide range of sub-100 nm-linewidth structures and devices, most recently MOSFETs [1,2], quantum wires [3,4] and lateral-surface superlattices [5]. In all but a few examples of such work the carbon K (C_K) x-ray line at 4.5 nm was used. The C_K line is attractive for nanolithography (i.e., sub-100 nm features) for two reasons: 1) a contrast of 10 db can be achieved in films of Au or W only 80 nm or 63 nm thick, respectively; 2) any loss of resolution due to photoelectrons should be minimal since their effective range is expected to be ~5 nm. On the other hand, use of the C_K line carries two significant

FOCUSED ION BEAM LITHOGRAPHY AND IMPLANTATION

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Abstract

During the past ten years a steady development of focused ion beam machines has taken place. A number of realistic applications in microelectronics have been demonstrated or identified. Typically machines operate at accelerating voltages between 10 and 150 kV with beam diameters down to 50 nm and current densities in the beam of 0.1 to 5A/cm^2. The ion species available include Ga and the main dopants of Si and GaAs (As, B, Si, and Be). Computer controlled patterning with 0.1 µm accuracy has been demonstrated. Photomask repair is already a commercially developed application. Integrated circuit restructuring and repair is a natural extension and is also being developed commercially.

In this paper we will survey ion beam lithography and maskless, resistless implantation. These applications generally demand the most sophisticated machinery including high voltage and mass separation, and so far they have been demonstrated only in the research laboratory. However, their long range impact may be significant. In lithography the absence of proximity effect and the ability to expose resist with fine features and vertical sidewalls without multilevel techniques offer distinct advantages. Focused ion beam implantation may, in special cases, be substituted for conventional fabrication, for example in CMOS threshold adjust and in special GaAs devices. The key issue of writing time will be examined.

Introduction

An energetic ion incident on a solid surface produces a number of physical effects: surface atoms can be sputtered off near the point of impact; the energy lost by the ion can produce chemical changes in adsorbed films or in the bulk of the solid; the ion can imbed itself in the solid changing its properties; the ion can displace lattice atoms from their equilibrium sites causing damage; and the ion can cause electrons to be emitted from the surface. Some of these effects such as sputtering and implantation are widely used in microfabrication where a flux of ions is incident on the wafer, part of which is masked by a lithographically patterned film structure (e.g. photoresist). Focused ion beams can address a given area of a wafer with submicrometer precision and remove the need for the lithography step. Thus the number of these ion/surface interaction modes to be exploited has increased.

The development of the liquid metal ion source[1,2] of high brightness made possible focused ion beam machines with usable current densities in the beam spot. Already in 1979 0.1 µm features were written with Ga ions with a current density in the beam of 1.5 A/cm^2. Ref. 3. The next important development was the use of alloy sources such as Au/Si/Be coupled with crossed electric and magnetic field mass separation.[4,5] This permitted the dopants of Si and GaAs to be focused on a surface.

Focused ion beam machines can be divided into two categories, those without mass-separation and those with mass separation.

Systems without mass separation are simpler and generally operate in the energy range of 10-70 kV. They have shown beam diameters below 0.05 µm and operate with Ga ions. The main applications are: ion milling for mask repair or for circuit restructuring and repair; ion induced deposition where adsorbed metal bearing molecules are broken up to form a patterned film on the surface; surface analysis (SIMS); and scanning ion microscopy which is used in aligning samples under the beam and is much like scanning electron microscopy.

The systems with mass separation generally operate up to 150 kV and use alloy sources. The mass separator can select out the desired ion species. Thus doubly ionized species are available up to 300 keV. The minimum beam diameters are near 0.05 µm. The main applications are lithography i.e. exposure of resist and maskless, patterned implantation. This paper will focus on the latter two applications only. A more complete review and references to the literature are found in ref. 6.

Machinery

1. System configuration:

The focused ion beam systems used in implantation and lithography are complex and, although two companies offer models for sale, they are still evolving.[7,8]*

The main component is the ion column, which uses a high brightness liquid metal alloy source to generate a beam of ions which passes through various elements which mass separate, focus and deflect the beam on the sample. A schematic of a column is shown in Fig. 1. The column sits on a vacuum chamber which houses a precise laser interferometrically controlled x-y stage. Pattern generation and deflection electronics position the stage and deflect the beam to produce a desired pattern with a desired dose.[7,8]

In general the machines look and operate very much like e-beam lithography machines except that an ion beam is used in place of an electron beam. Figs. 2 and 3 show the two commercial models available.

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*In fact simpler non-mass separated columns can, and have been used for lithographic writing of features down to 30 nm. However, since Ga is used the resist thickness which can be exposed is limited. See ref. 24.

Proceedings of 8th Biennial University/Govt./Industry Microelectronics Symp. Westboro, Mass. June, 1989 (published by IEEE)

Resonant Tunneling Across and Mobility Modulation Along Surface-Structured Quantum Wells

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Abstract

We present results of fabrication and transport measurements on surface-structured quantum wells. The structures are fabricated on GaAs/AlGaAs modulation-doped layers. Three different devices are examined: the grid-gate lateral-surface-superlattice, the planar-resonant-tunneling field-effect transistor, and the multiple parallel quantum wires. In the first two structures, transport is perpendicular to the field induced potential barriers. At 4.2 K, we observed evidence for resonant tunneling in both types of devices. In the third type of structure, transport is through isolated quantum wires parallel to the barriers. The presence of one-dimensional energy subbands, and mobility modulation, above and below the two-dimensional value, were observed.

Submitted to J. Vac. Sci. Technol. B, (To be published Nov/Dec. 1989)

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